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To my past, present, and future family.

"You're braver than you believe, and stronger than you seem, and smarter than you think."

- A.A. Milne, Christopher Robin

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"If you don't know, the thing to do is not to get scared, but to learn."

- Ayn Rand, Atlas Shrugged

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"It's the job that's never started as takes longest to finish."

- J.R.R. Tolkien, The Lord of the Rings

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"I am a wife-made man."

- Danny Kaye

"I knew when I met you an adventure was going to happen."

- A.A. Milne, Winnie the Pooh

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The Standard Model

This chapter outlines the theoretical and mathematical concepts of modern particle physics. The Standard Model (SM) is the well-tested and most successful theory to describe the nature of the elementary particles and their interactions. An overview of the SM is given in the Section 2.1. More detail about the SM can be found in various

The theories and discoveries of thousands of physicists since the 1930s have resulted in a remarkable insight into the fundamental structure of matter: everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our best understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model of particle physics. Developed in the early 1970s, it has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments, the Standard Model has become established as a well-tested physics theory.

2.1 The Standard Model of Particle Physics

Developed in the early 1970s, the Standard Model of particle physics has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena. It is currently the most accurate description of elementary particles and their interactions. It presents a combination of quantum mechanics and relativity theory to form a relativistic quantum field theory of the particles and the forces of our nature.

Matter particles

All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or generations. The lightest and most stable particles make up the first generation, whereas the heavier and less stable particles belong to the second and third generations. All stable matter in the universe is made from particles that belong to the first generation; any heavier particles quickly decay to the next most stable level. The six quarks are paired in the three generations the up quark and the down quark form the first generation, followed by the charm quark and strange quark, then the top quark and bottom (or beauty) quark. Quarks also come in three different colours and only mix in such ways as to form colourless objects. The six leptons are similarly arranged in three generations the electron and the electron neutrino, the muon and the muon neutrino, and the tau and the tau neutrino. The electron, the muon and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass. Forces and carrier particles

There are four fundamental forces at work in the universe: the strong force, the weak force, the electromagnetic force, and the gravitational force. They work over different ranges and have different strengths. Gravity is the weakest but it has an infinite range. The electromagnetic force also has infinite range but it is many times stronger than gravity. The weak and strong forces are effective only over a very short range and dominate only at the level of subatomic particles. Despite its name, the weak force is much stronger than gravity but it is indeed the weakest of the other three. The strong force, as the name suggests, is the strongest of all four fundamental interactions. Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called bosons. Particles of matter transfer discrete amounts of energy by exchanging bosons with each other. Each fundamental force has its own corresponding boson the strong force is carried by the gluon, the electromagnetic force is carried by the photon, and the W and Z bosons are responsible for the weak force. Although not yet found, the graviton should be the corresponding force-carrying particle of gravity. The Standard Model includes the electromagnetic, strong and weak forces and all their carrier particles, and explains well how these forces act on all of the matter particles. However, the most familiar force in our everyday lives, gravity, is not part of the Standard Model, as fitting gravity comfortably into this framework has proved to be a difficult challenge. The quantum theory used to describe the micro world, and the general theory of relativity used to describe the macro world, are difficult to fit into a single framework. No one has managed to make the two mathematically compatible in the context of the Standard Model. But luckily for particle physics, when it comes to the minuscule scale of particles, the effect of gravity is so weak as to be negligible. Only when matter is in bulk, at the scale of the human body or of the planets for example, does the effect of gravity dominate. So the Standard Model still works well despite its reluctant exclusion of one of the fundamental forces. So far so good, but...

...it is not time for physicists to call it a day just yet. Even though the Standard Model is currently the best description there is of the subatomic world, it does not explain the complete picture. The theory incorporates only three out of the four fundamental forces, omitting gravity. There are also important questions that it does not answer, such as What is dark matter?, or What happened to the antimatter after the big bang?, Why are there three generations of quarks and leptons with such a different mass scale? and more. Last but not least is a particle called the Higgs boson, an essential component of the Standard Model. On 4 July 2012, the ATLAS and CMS experiments at CERN's

Large Hadron Collider (LHC) announced they had each observed a new particle in the mass region around 126 GeV. This particle is consistent with the Higgs boson but it will take further work to determine whether or not it is the Higgs boson predicted by the Standard Model. The Higgs boson, as proposed within the Standard Model, is the simplest manifestation of the Brout-Englert-Higgs mechanism. Other types of Higgs bosons are predicted by other theories that go beyond the Standard Model. On 8 October 2013 the Nobel prize in physics was awarded jointly to Franois Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider." So although the Standard Model accurately describes the phenomena within its domain, it is still incomplete. Perhaps it is only a part of a bigger picture that includes new physics hidden deep in the subatomic world or in the dark recesses of the universe. New information from experiments at the LHC will help us to find more of these missing pieces.

Chapter 3

The ATLAS Experiment at LHC

The European Organization for Nuclear Research (CERN[1]) was founded in 1954 and is based in the suburb of Geneva on the Franco–Swiss border. The main function of CERN is to provide particle accelerators and detectors for high-energy physics research. The physicists and engineers at CERN are probing the fundamental structure of the universe using the world's largest and most complex scientific facility — the Large Hadron Collider (LHC) [3]. In the LHC, the particles are boosted to high energies and collide at close to the speed of light. The results of the collisions are recorded by the various detectors. There are seven experiments at the LHC. The biggest of these experiments are ATLAS (A Toroidal LHC ApparatuS) [2] and CMS (Compact Muon Solenoid) [4] which use general-purpose detectors to investigate a broad physics programme ranging from the search for the Higgs boson to extra dimensions and particles that could make up dark matter. The ALICE (A Large Ion Collider Experiment) [5] experiment is designed to study the physics of quark-gluon plasma form and the LHCb (Large Hadron Collider beauty) [6] experiment specializes in investigating of CP violation by studying the b-quark. These four detectors sit underground in huge caverns of the LHC ring. The rest three experiments, TOTEM [7], LHCf [8], and MoEDAL [9], are smaller. The TOTEM (TOTal Elastic and diffractive cross section Measurement) [7] experiment aims at the measurement of total cross section, elastic scattering, and diffractive dissociation. The LHCf (Large Hadron Collider forward) [8] experiment is intended to measure the neutral particle produced by the collider using the forward particles. The prime motivation of the MoEDAL (Monopole and Exotics Detector at the LHC) [9] experiment is to search directly for the magnetic

[1]The name CERN is derived from the acronym for the French Conseil Européen pour la Recherch Nucléaire

monopole.

3.1 The Large Hadron Collide

The LHC [3] is the world's largest and most powerful accelerator which accelerates and collides protons in a 26.7 km circumference crossing the Franco–Swiss border 100 m underground. Built in the tunnel of the former LEP (Large Electron–Positron), the LHC is capable of colliding protons as well as heavy ions. Comparing with the LEP which collides electrons and positrons, the advantage of the LHC is the lower energy loss [2] in the synchrotron radiation, such that higher energies can be reached by the LHC. The LHC is designed for collisions at a centre-of-mass energy $\sqrt{s} = 14$ TeV and an instantaneous luminosity of $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}. Figure 3.1 shows the infrastructure of the LHC and the pre-accelerator system.

The protons are extracted by ionization from a hydrogen source and are accelerated to 50 MeV by the linear accelerator LINAC2. Then they are injected into the Proton Synchrotron Booster (PSB) where the proton energies are increased to 1.4 GeV before they enter the Proton Synchrotron (PS) which accelerates the protons to 25 GeV. Next, the proton energies are increasing to 450 GeV in the Super Proton Synchrotron (SPS). Finally, the protons are split into two beams and enter the LHC where the two beams run in two adjacent beam pipes with opposite directions. In order to keep the protons on the circular trajectory in the LHC, 1232 superconducting dipole magnets [10] generate a magnetic field strength of 8.33 T to bend the proton beams in eight arcs. Additionally, 392 quadrupole magnets [10] are installed to focus the beam. A cryogenic system running with super-fluid helium-4 is used to cool down the superconducting magnets to a temperature

[2]The energy loss for protons is about eleven orders of magnitude smaller than the electrons

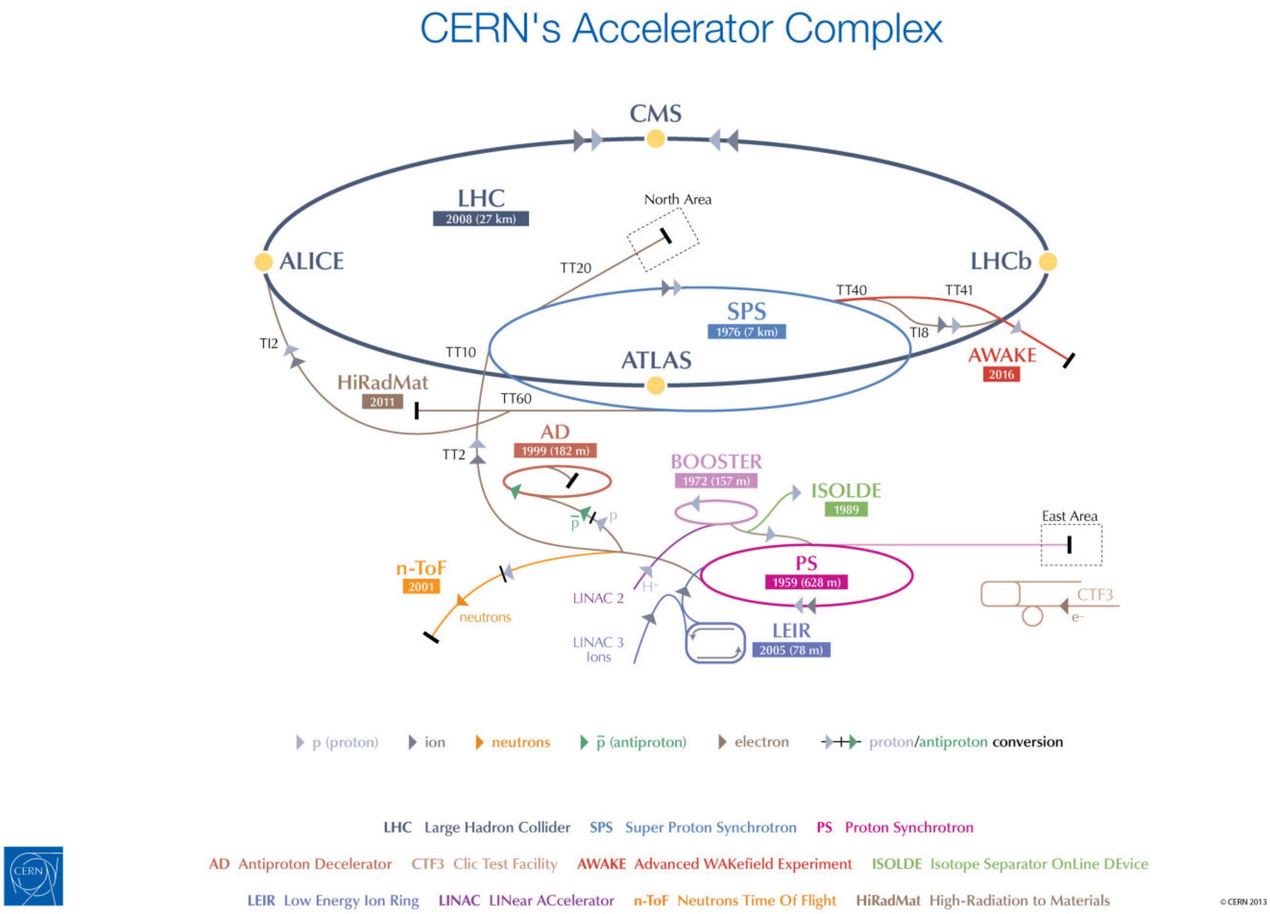

Figure 3.1: The accelerator complex at CERN [1].

of 1.7 K.

For a given physics process, the event rate is proportional to the cross section σ of this process.

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma \tag{3.1}$$

where N is the number of events and $\mathcal{L}$ denotes the luminosity of the beam. The luminosity of the beam, $\mathcal{L}$ can be calculated by

$$\mathcal{L} = \frac{N^2 f}{4\pi\sigma_x\sigma_y} \cdot F \tag{3.2}$$

where N is the number of protons, f is the bunches crossing frequency, and the σ_x and σ_y are the x and y components for cross section σ. The geometric luminosity reduction factor, F, is related to the crossing angle at the Interaction Point (IP). Considering a beam consisting of 1.15×10^{11} protons with bunching spacing of 25 ns, the transversal size of the bunch at Interaction Pointe 16×10^{-4} cm, and taking the geometric luminosity reduction factor as 1, the design luminosity of 10^{34} cm^{-2}s^{-1} can be reached.

The first beam was circulated through the collider on the morning of 10 September 2008 [11]. However, a magnet quench incident occurred on 19 September 2008 and caused extensive damage to over 50 superconducting magnets, their mountings, and the vacuum pipe. Most of 2009 was spent on repairs the damage caused by the magnet quench incident and the operations resumed on 20 November of that year. The first phase of data-taking (Run 1) started at the end of 2009 and the beam energy was increased to a centre-of-mass $\sqrt{s} = 7$ TeV in 2011 and $\sqrt{s} = 8$ TeV in 2012. The total integrated luminosity of 5.46 fb^{-1} was collected in 2011 and of 22.8 fb^{-1} was collected in 2012. Since 13 February 2013 the LHC was in the Long Shutdown 1 (LS1) phase for maintenance and upgrades. On 5 April 2015, the LHC restarted and was operating at a centre-of-mass energy $\sqrt{s} = 13$

TeV throughout the Run 2 phase[3].

3.2 The ATLAS experiment

The ATLAS[4] detector is a multi-purpose detector housed in its cavern at point 1 at the LHC. It is the largest experiment at the LHC with a length of 44 m, a diameter of 25 m, and a weight of approximately 7 000 tonnes. It consists of three high precision sub-detector systems which are arranged concentrically around the interaction point and in forward and backward symmetrically. Related to this symmetry, the ATLAS detector is sectioned into the central barrel region with one end-cap region perpendicular to the beam pipe on either side. Figure 3.2 shows an overview of the ATLAS detector with its major components.

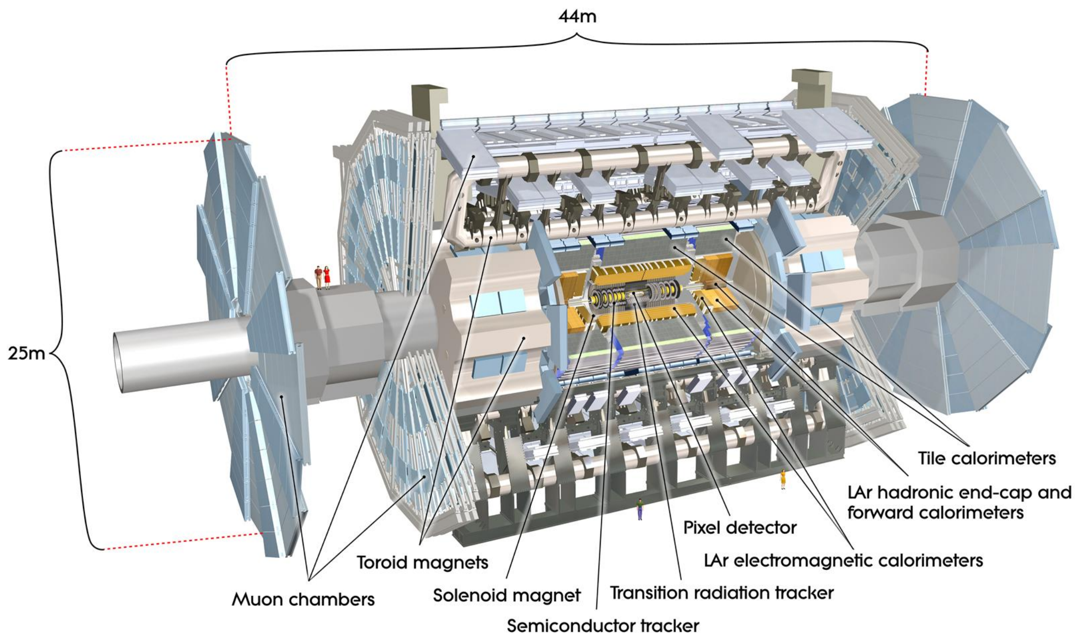

Figure 3.2: Overview of the ATLAS detector

[3]The Run 2 data-taking started from 2015
[4]A Toroidal LHC Apparatus

The ATLAS detector is designed to record the proton-proton interactions delivered by the LHC. It can identify particles and measure their tracks and energies with very high precision, therefore, it is sensitive to large areas of particle physics phenomena from the precision measurement of the Standard Model (SM) to beyond the SM. The detector is constituted by three sub-detector systems and the magnet system. The innermost part of the detector is called the inner detector which identifies and reconstructs the charged particles as well as the primary and secondary vertices. Around it, the calorimeter system is built as a cylindrical barrel with caps at each end to measure the particle energies. The detector is completed by the muon spectrometer which performs identification and measurement of momenta of muons. The magnetic system produces a field of B = 0.5 T and B = 1 T at barrel and two end-cap, respectively. The detector has to withstand large collision rates with approximately 1000 particles per collision, therefore, a fast readout and a three-level trigger system are implemented to reduce the event rate from 40 MHz to 200 Hz. The ATLAS coordinate system and the detail of each sub-detector systems are described in the following sections.

3.2.1 The ATLAS coordinate system

ATLAS uses a right-handed coordinate system with its origin at the nominal proton-proton interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. Along the z-axis the detector is divided into side-A (positive z) and side-C (negative z). The positive x-axis is defined by the direction pointing from the IP to the centre of the LHC ring, and the positive y-axis points upward.The azimuthal angle ϕ is measured around the beam pipe and the polar angle θ is the angle from the z-axis. The transverse momentum p_{T}, the transverse energy E_{T} and the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ are defined in the transverse plane[5], here exemplary for p_{T}:

$$p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2} \tag{3.3}$$

An important quantity in hadron collider physics is the **rapidity**, y, because of the invariance y under Lorentz boosts in the longitudinal direction. The rapidity is defined as

$$y = \frac{1}{2} \ln \left[\frac{E + p_z}{E - p_z} \right] \tag{3.4}$$

where E denotes the particle energy and p_z is the component of the momentum along the beam direction. Since mainly leptons can be considered massless in respect to the nominal centre-of-mass energy, the pseudorapidity, η, is used in stead of using the y. For a massless particle, the **pseudorapidity**, η, depends on the polar angle θ through:

$$\eta = -\ln \tan \frac{\theta}{2} \tag{3.5}$$

For a particle with the energy E much larger than its mass, the approximation $E \approx |\vec{p}|$ is valid. The distance, ΔR, between two objects in the $\eta - \phi$ plan is given by

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \tag{3.6}$$

where $\Delta\eta$ and $\Delta\phi$ are the difference in pseudorapidity and azimuthal angle, respectively.

3.2.2 The Inner Detector and Tracking System

3.2.3 The Calorimeter

3.2.4 The Muon Spectrometer

The outermost part of the ATLAS detector is the Muon Spectrometer [2] [12] [13]. Muons have the same properties as electrons but 200 times heavier than the electrons and

[5] $x - y$ plane

muons don't interact predominately by Bremsstrahlung but have minimal ionizing at LHC energy in the inner layers of the detector. Only the muons with an energy less than 5 GeV are stopped before the Muon Spectrometer. Therefore, muons are the only measurable particles that can penetrate the Inner Detector and the Calorimeters. In order to determine the muon momentum with high precision, a detector that concentrates on the measurement of muons is necessary.

The Muon Spectrometer is designed to measure the transverse momentum (p_{T}) of muons with $p_{\mathrm{T}} > 3$ GeV with a resolution of 3% for $p_{\mathrm{T}} < 250$ GeV and increasing to 10% at 1 TeV. It consists of large toroid magnets system and three layers of high precision tracking chambers which allow a precise measurement of the muon momentum over nearly the full solid angle. The barrel toroid magnet system is composed of eight superconducting coils which are installed radial symmetrically around the beam pipe. It covers the range $|\eta| < 1.4$ and bends the trajectories of muons with the bending power 1.5 to 5.5 Tm. The magnetic field produced by the barrel toroid magnets provides an approximately 1 T field at the center of each coils, but is rather non-uniform, especially in the barrel-endcap transition region. In the endcap toroid magnets system, the magnetic field is provided by eight superconducting coils, closed in an insulation vessel extending to about 10 m in diameter, located between the first and the second station of tracking chambers. The endcap toroid magnets cover $1.6 < |\eta| < 2.4$ and provide a a magnetic field in the range of 1 to 2 T with bending power 1 to 7.5 Tm.

The Monitored Drift Tubes (MDTs) consists of cylindrical drift tubes, filled with a gas mixture of argon and carbon dioxide. A tungsten-rhenium alloyed aluminium wire in the centre of each tube collects the electrons freed by ionization of the gas volume by traversing muons. The MDTs covers a full range of $|\eta| < 2.7$, while the inner layer only covers $|\eta| < 2.0$. The Cathode Strip Chambers (CSCs) provides a coverage range $2.0 < |\eta| < 2.7$, where MDTs would have occupancy problems. Both MDTs and CSCs are used for precision tracking in the spectrometer bending plane and end-cap inner layer, respectively. The Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) are used for triggering in barrel and end-cap, they have sufficient intrinsic time resolution of 1.5 ns and 4 ns, respectively. A sketch of the Muon Spectrometer and its four components are depicted in Figure 3.3 and Table 3.1 gives a summary of the Muon Spectrometer components

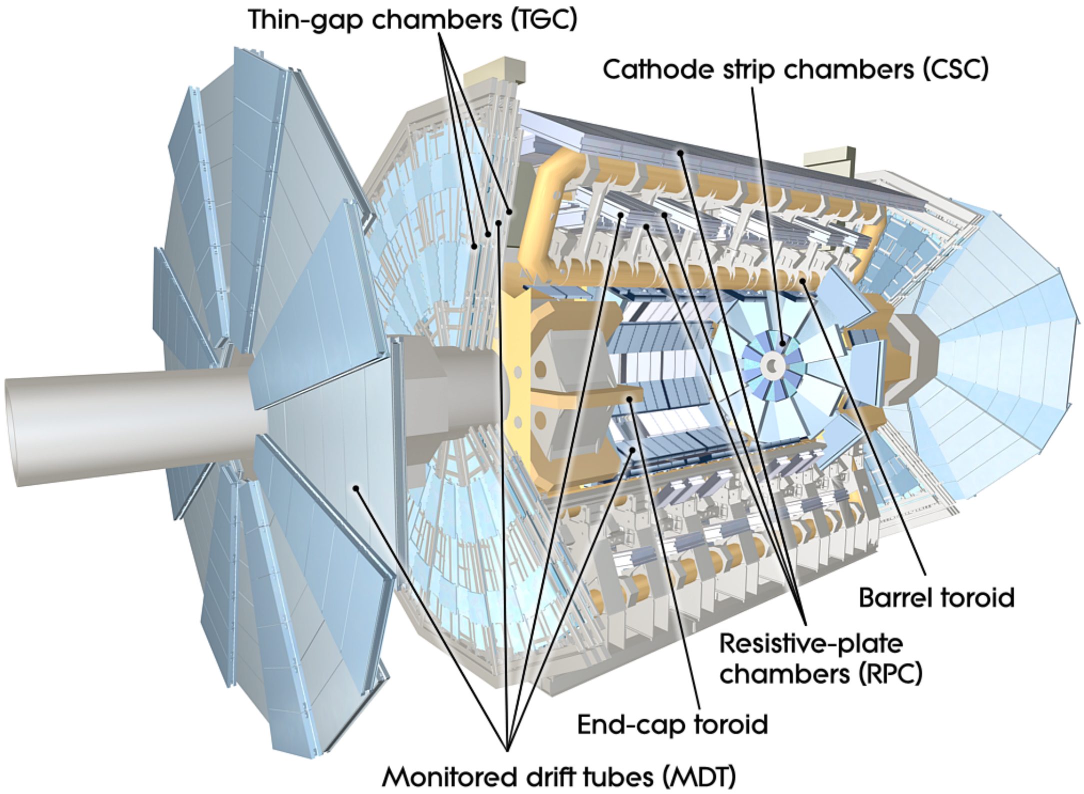

Figure 3.3: Sketch of the muon system of the ATLAS detector [2].

3.2.5 The Trigger System and Data Acquisition

3.2.6

Type	Purpose	Location	η coverage	Channel
MDT	Tracking	barrel + end-cap	$0.0 < \eta < 2.7$	354k
CSC	Tracking	end-cap layer 1	$2.0 < \eta < 2.7$	30.7k
RPC	Trigger	barrel	$0.0 < \eta < 1.0$	373k
TGC	Trigger	end-cap	$1.0 < \eta < 2.4$	318k

Table 3.1: A summary of the Muon Spectrometer components.

Chapter 4

The Electron Isolation Efficiency and Scale Factors

Chapter 5

The Real Lepton Efficiencies

Chapter 6

Conclusion

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